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14. ABSTRACT
We are investigating the crustal and upper mantle structure of the region in central Asia bounded approximately by longitude 41-67°E and latitude 20-44°N by using in-country datasets of seismic phase arrival times, supplemented by ground truth datasets developed from our previous research efforts. We present the results of *Pn* tomography using a dataset consisting entirely of GT5 events in the region. From 27 calibrated earthquake clusters we extract 832 events that qualify as ground truth (GT)5 at the 90% confidence level. The raypaths of *Pn* readings from these events provide good coverage of most of the region except for the Makran region in the southeast. To determine an appropriate reference model for the region we compared empirical travel times calculated from the GT5 dataset to those predicted by several models: the ak135 global model (Kennett et al., 1995), the CUB2.0 model (Ritzwoller et al., 2003), and the so-called "Unified" model a 3-D velocity model of the crust and upper mantle in Eurasia, constructed from models developed by researchers at Lawrence Livermore National Laboratory (LLNL) and Los Alamos National Laboratory (LANL) (Pasyanos et al, 2004; Begnaud et al., 2004; Steck et al., 2004; Flanagan et al., 2007). Although the CUB2.0 and Unified models do vary laterally, in the study region they vary quite slowly and capture little of the variability of observed travel times. All three models predict *Pn* travel times that are systematically too fast. These baseline errors range from 2-4 seconds. For this initial round of tomography we stretched the ak135 model to a crustal thickness of 45 km for the reference model.

Tomography is first performed in a "traditional" way, allowing for individual event corrections as well as station corrections. Through relative event relocation, however, these clusters of GT5 events have very strong constraints on relative location, depth, and origin time of the associated earthquakes. For each cluster, then, we can assign a single "cluster correction". This dramatically reduces the number of free parameters and stabilizes the inversion. This exercise helps reveal problems in the GT5 dataset that can in some cases (e.g., erroneous station coordinates) be corrected, enhancing the value of the GT5 dataset for validation of tomography based on larger, uncalibrated datasets. It also reveals patterns in *Pn* velocities in the study region which have much shorter wavelength than previous studies. We also investigated the possible contribution of crustal thickness variations to account for the observed variability of empirical travel times for *Pn*. The experiment is based on a simple model of a single-layer crust over a halfspace. A digital terrain map is filtered at 100 km and converted to Moho depth, under the asumption of full isostatic compensation, which is almost certainly an over-estimate. For reasonable density contrast the Moho depth variation is about 5 times the topography. For a set of raypaths based on the locations of the actual events in the GT dataset and actual stations we calculate the *Pn* travel time through the crust and along the crust-mantle boundary of the perturbed model and also through the unperturbed flat-layered model, and take the difference. The variance of these differences is about 4% of the variance of observed Pn travel times in the study region, suggesting that crustal thickness variations contribute only at a low level to the observed variability. Most of the variability in Pn travel times presumably arrises from lateral variations in bulk velocity, perturbations to the ray paths caused by those lateral variations, errors in cluster calibration, and phase identification errors.

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CRUSTAL STRUCTURE FROM IN-COUNTRY AND GROUND-TRUTH DATA

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ABSTRACT

We are investigating the crustal and upper mantle structure of the region in central Asia bounded approximately by longitude 41-67°E and latitude 20-44°N by using in-country datasets of seismic phase arrival times, supplemented by ground truth datasets developed from our previous research efforts. We present the results of *Pn* tomography using a dataset consisting entirely of GT5 events in the region. From 27 calibrated earthquake clusters we extract 832 events that qualify as ground truth (GT)5 at the 90% confidence level. The raypaths of *Pn* readings from these events provide good coverage of most of the region except for the Makran region in the southeast. To determine an appropriate reference model for the region we compared empirical travel times calculated from the GT5 dataset to those predicted by several models: the ak135 global model (Kennett et al., 1995), the CUB2.0 model (Ritzwoller et al., 2003), and the so-called "Unified" model a 3-D velocity model of the crust and upper mantle in Eurasia, constructed from models developed by researchers at Lawrence Livermore National Laboratory (LLNL) and Los Alamos National Laboratory (LANL) (Pasyanos et al, 2004; Begnaud et al., 2004; Steck et al., 2004; Flanagan et al., 2007). Although the CUB2.0 and Unified models do vary laterally, in the study region they vary quite slowly and capture little of the variability of observed travel times. All three models predict *Pn* travel times that are systematically too fast. These baseline errors range from 2-4 seconds. For this initial round of tomography we stretched the ak135 model to a crustal thickness of 45 km for the reference model.

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OBJECTIVES

This research has the goal of developing in-country datasets that can be used to improve ground-bascd monitoring capabilities in the study region, by providing information needed to develop and tcst more accurate travel time models for seismic phases that propagate in the crust and upper mantle. The main dataset to be produced is a bulletin of earthquakes in the region at magnitudes of 2.5 and higher, associated with readings from seismograph stations operating in-country for the period 1995–2005. These events and readings will be integrated with the best available catalog of regional seismicity for that period that includes associated regional and teleseismic phase arrival times. All events will be relocated, carefully reviewed, and calibrated, where possible, with ground truth data. We will conduct preliminary modeling experiments with these data, using *Pn/Sn* tomography to image broad-scale features of the crust and upper mantle in the region. The tomographic experiments will also help reveal problems in the datasets of earthquake locations and phase identifications, and thus serve a quality control function. The resulting datasets and model results will provide a solid foundation for further research.

RESEARCH ACCOMPLISHED

In-Country Data

The main sources of in-country data are the seismic networks operated by the International Institute of Earthquakc Engineering and Seismology (IIEES) and the University of Tehran Institute of Geophysics (UTIG). We have acquired all phase reading data from these networks through 2005, and integrated the data with other readings from regional and global networks. We have also acquired phase reading data from 2005 through 2008 for both networks but this data is still being processed.

We have also acquired independent datasets of phase readings from the Oman network (2004–2007) (Figure 1) and the Kuwait network (2000-2008) for earthquakes in the study region and these are being merged with other readings. The Oman data in particular is of great valuc for improving location accuracy in the southernmost part of the study region.

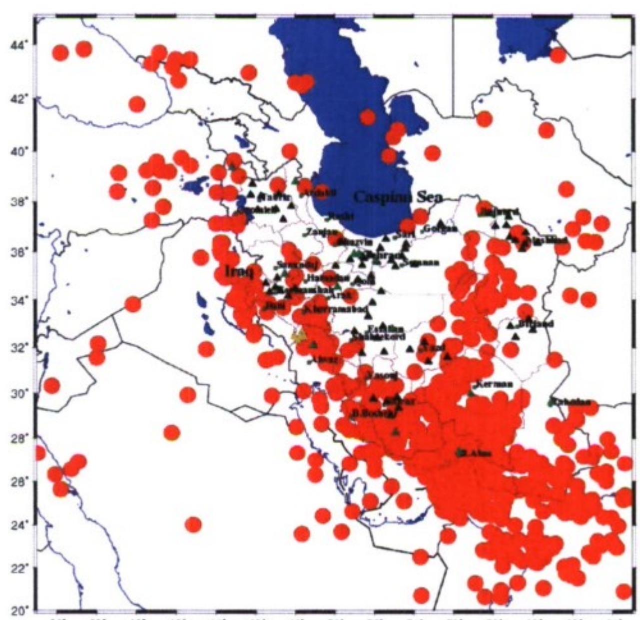

Figure 1. Locations of events determined by the Oman network during 2005-2007, for which phase readings have been acquired. These network locations are extremely poor and it is a difficult task to properly associate these readings with well-constrained events in our main catalog.

Our colleagues in the region have been conducting careful rcanalysis of events in certain parts of the rcgion, repicking all readings and relocating events. We havc acquired these datasets for the Tehran, Zanjan, and Tabriz regions (Figures 2 and 3). These datasets have been very valuable for our location calibration studies in these regions.

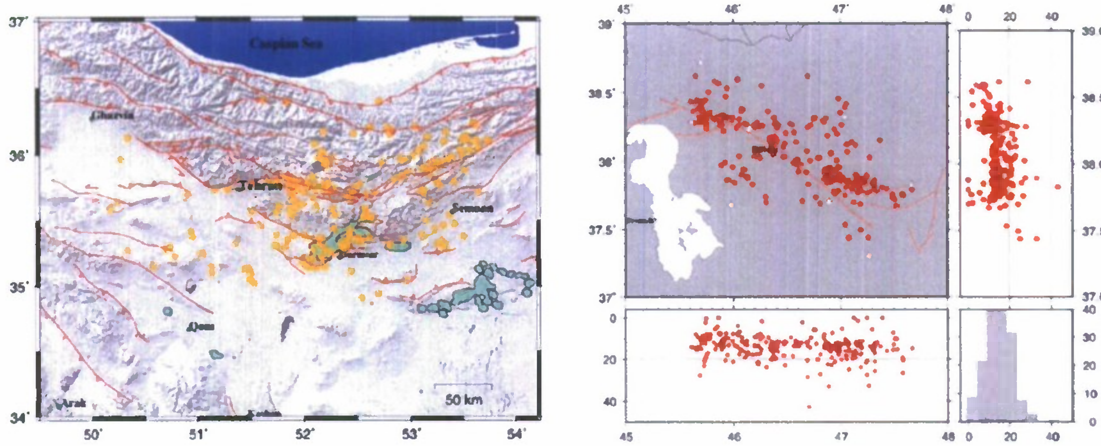

Figure 2. Seismicity in the Left) Tehran region and Right) Tabriz region, from a specialized study involving repicking all waveforms, combining all available in-country data, and relocating. This work is done by our colleagues in-country.

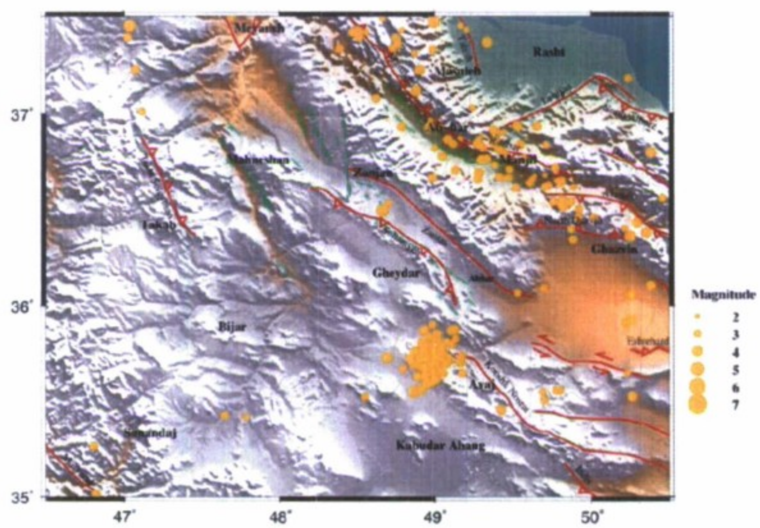

Figure 3. Seismicity in the Zanjan region from a specialized study involving repicking all waveforms, combining all available in-country data, and relocating. This study produced a large number of new events for the Avaj cluster. This work is done by our colleagues in-country.

Finally, we have acquired from colleagues several valuable datasets of phase readings from temporary deployments that are extremely valuable for our location calibration studies.

Catalog of Earthquakes

Our latest update to the catalog of seismicity in the region includes 26,973 events from 1923 through December 2008. Events with magnitude 2.5 or larger are retained. Some events with unknown magnitude are retained if they can be reliably located. For the major sources of data the current catalog's completeness is given below:

- International Seismological Centre (ISC): complete through 2006.
- U.S. Geological Survey Preliminary Determination of Epicenters (PDE): complete through 2008.
- UTIG: complete through 2005. We have the full catalog for 2006-2008 and it will be merged with the catalog.

- IIEES: complete through 2008 for data reported to the ISC, but not all readings are reported that way. We have the full IIEES catalog through 2008 and it will be merged with the catalog.

A subset of 7592 events from this catalog which satisfy the condition that secondary azimuth gap (largest azimuth filled by a single station) is less than 180° are shown in Figure 4.

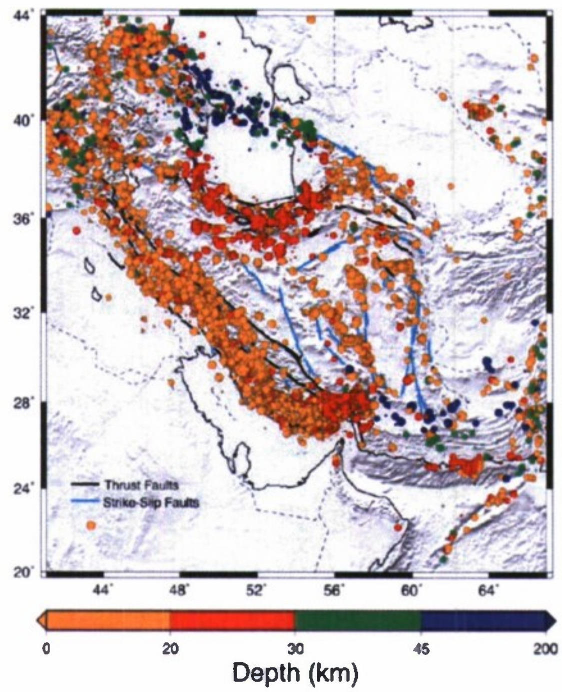

Figure 4. A subset of earthquakes from our earthquake catalog in the study region, showing the locations of 7592 events that satisfy the requirement that secondary azimuth gap is less than 180°. The epicenters of these events are therefore better constrained than other events in the catalog, even though the locations are not calibrated. Focal depths are color-coded.

Calibrated Locations

We have been building our dataset of calibrated earthquake clusters in the study region through several projects spanning about 10 years. We now have 28 earthquake clusters, containing 1,271 earthquakes, in the region that are calibrated in location and 27 of those are also calibrated in origin time (Figure 5). These 28 clusters contain 832 events that qualify as $GT5_{90}$ or better.

The latest clusters that we have calibrated are Tiab, Fin, Siah-Kuh, Qom, Aradan, and Ardebil. We have data with which several other clusters can be calibrated as well, and these are in process.

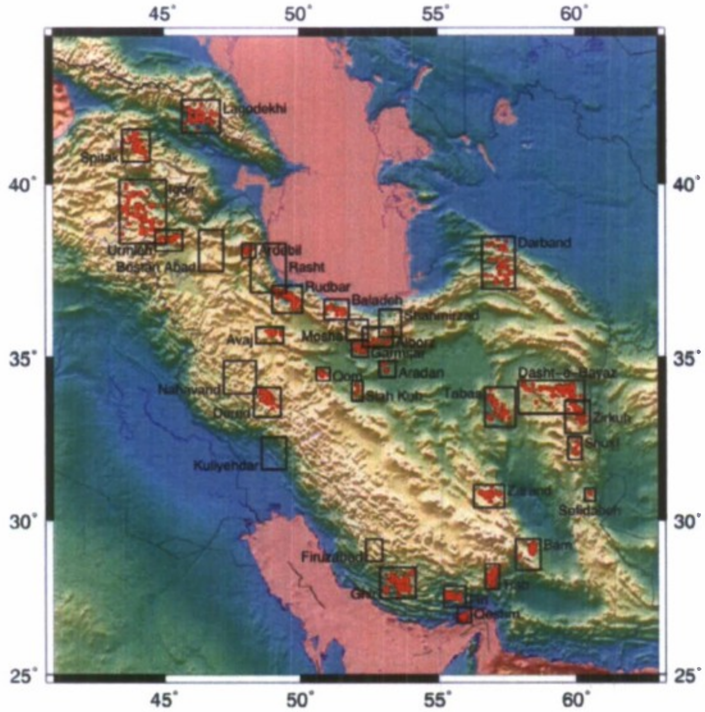

Figure 5. Locations of earthquake clusters with calibrated locations and, in most cases, origin times. Epicenters shown by red circles. Boxes without epicenters indicate clusters whose calibration analysis is in process.

Pn Tomography

Our goal in conducting tomographic experiments with our data is two-fold: 1) to obtain a better image of first-order variations in crustal and upper mantle structure in the region; and 2) to use the results of tomography to reveal outliers in our dataset that may indicate errors in our calibration work or in phase identification. The results we show here deal mainly with the first effort. Tomography is conducted with the method described by Ritzwoller et al. (2002). Only *Pn* tomography has been attempted so far.

A Baseline Model

For our initial tomographic studies, in which we are trying to obtain a reasonable base model for more detailed studies with the full dataset of arrival time readings, we use only *Pn* readings from events that are calibrated to $GT5_{90}$ or better. Before any tomography was performed, we simply compared the predicted travel times through several reference models to the empirically-determined travel times from our GT dataset (Figure 6). The comparisons shown here were done for a single source region (the Dorud cluster, Figure 5), sampling paths to existing seismic stations in the study region.

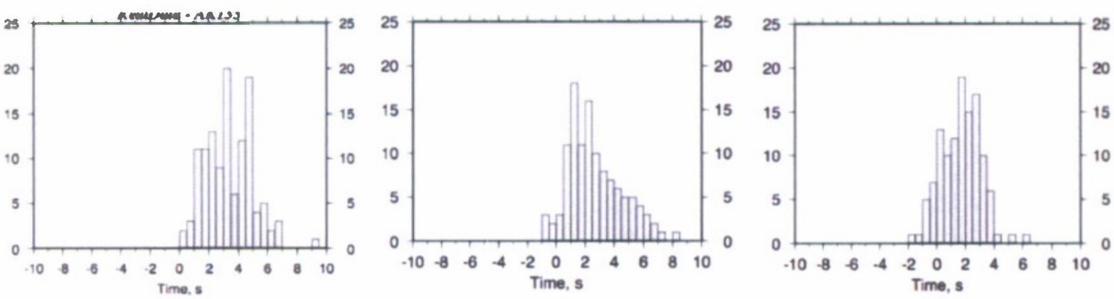

Figure 6. Histograms of the residuals against our GT dataset for the Dorud cluster of predicted travel times for Pn through Left) ak135, Center) CUB2.0, and Right) Unified model.

All three models are too fast by 2–4 seconds on average, compared to the GT dataset travel times. The three primary sources for these discrepancies are 1) average crustal thickness which is too small, 2) average crustal velocities that are too high, and 3) average upper mantle *Pn* velocities that are too high. *Pn* data alone provide only very weak resolving power between these factors, and so we try to use information from other sources to place some constraints on a baseline model.

One such constraint comes from numerous studies (e.g., Doloei and Roberts, 2003; Sodoudi et al., 2004; Mokhtari et al. 2004; Kaviani et al., 2007) that indicate Moho depth in the study region ranges over 40-55 km. Therefore it is likely that the residuals of the ak135 model (which has a 35-km thick crust) against the GT dataset are partly the result of a too-thin crust. A model in which the two crustal layers of ak135 are stretched proportionally to a total thickness of 45 km improves the fit to observed *Pn* travel times, but there is still a systematic positive residual. We next decreased the crustal velocities by 10%, which gives a good average fit to the observed *Pn* data (Figure 7)

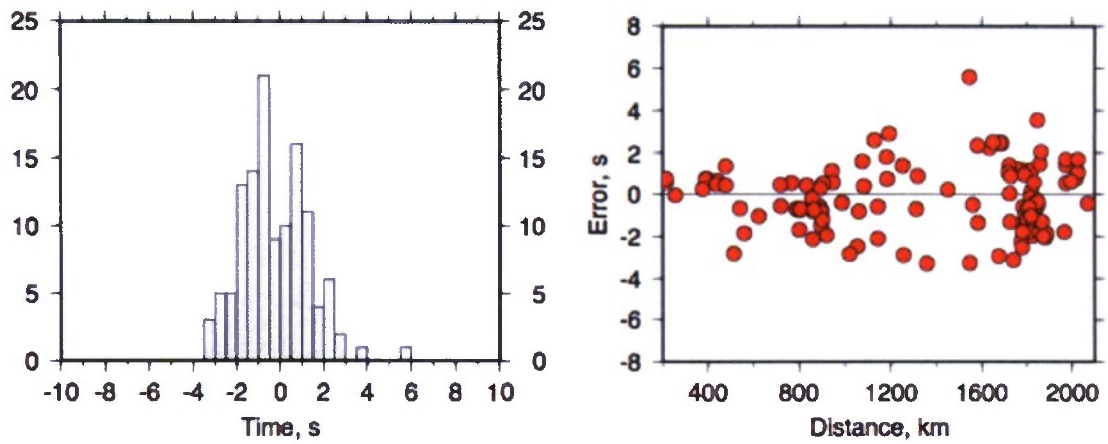

Figure 7. Left) Histogram of residuals against out GT dataset of predicted travel times for *Pn* with a model based on the ak135 model with crustal layers stretched proportionally to a total thickness of 45 km and crustal velocities reduced by 10%. Right) Same residuals plotted as a function of epicentral distance, showing that there is no trend with distance that would indicate the need for a different average *Pn* velocity in the model.

The fact that there is no evidence of distance-dependent trend in the residuals in Figure 7 indicates that the ak135 *Pn* velocity (8.045 km/s) is a reasonable average for this source region. This baseline model is derived for one source region in the study region. We will repeat the exercise with other source regions, and with the entire GT dataset, in order to better understand the variability of such models across the study region and to derive a full-region baseline model for *Pn* tomography with larger datasets. It is not yet clear if we will be able to use a single crustal thickness across the entire region, or whether we will adopt a baseline model which incorporates some degree of variability in Moho depth. The issue of Moho depth variations as it relates to *Pn* tomography is further considered below.

Event Corrections vs. Cluster Corrections

In standard *Pn* tomography studies, a source correction term is allowed for each earthquake source to absorb errors in assumed location, focal depth, and origin time, as well as near-source crustal velocity variations. This adds a large number of free parameters to the problem. In our case however, the multiple event relocation algorithm we use to develop clusters of calibrated earthquake locations provides very string constraints on the relative locations and origin times of the events in a given cluster. Therefore, we can reduce the number of free parameters dramatically by specifying a "cluster correction" which is common to all events in each cluster. The consequence of doing tomography with the two types of correction is shown in Figure 8.

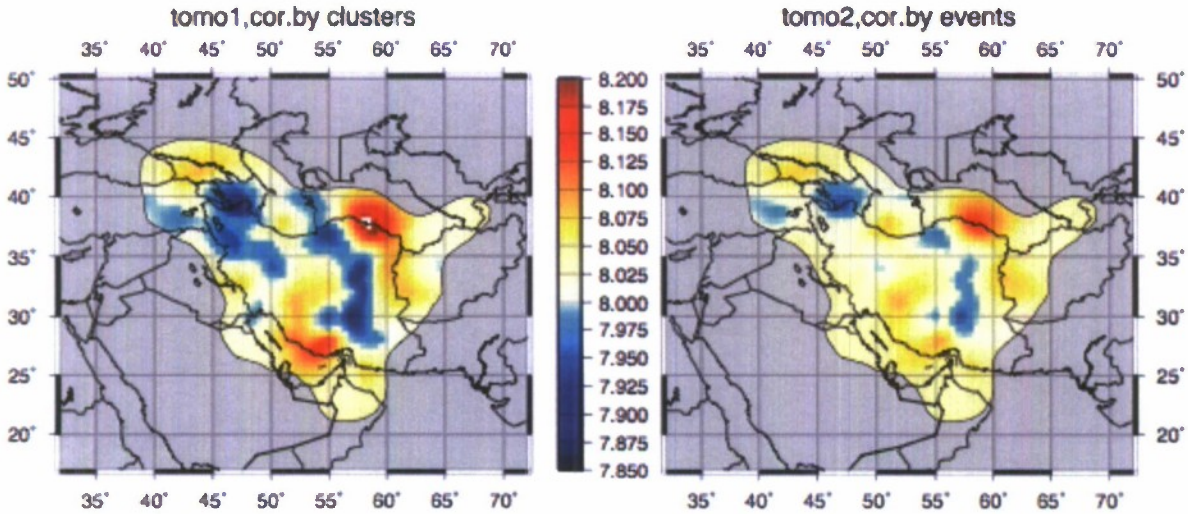

Figure 8. Comparison of *Pn* tomography done with Left) cluster corrections, and Right) event corrections, using 6,135 *Pn* raypaths from GT5 events to stations in the region. The clipping region, within which results are shown in color, is defined by a raypath density of at least 50 rays within a 2°x2° cell.

The use of event corrections clearly allows them to absorb some of the signal that would otherwise be reflected in greater variations in *Pn* velocity. The reduction in velocity variations when using event corrections is about 0.3%.

Relative Importance of Source and Station Corrections

We carried out several tomographic studies to determine the relative importance of source corrections (i.e., cluster corrections) and station corrections, which mainly account for departures of the crustal velocities from those of our model. The reference model is ak135, stretched to have a 45 km crustal thickness, retaining ak135 crustal velocities. The consequence of using no source or station corrections is shown in Figure 9.

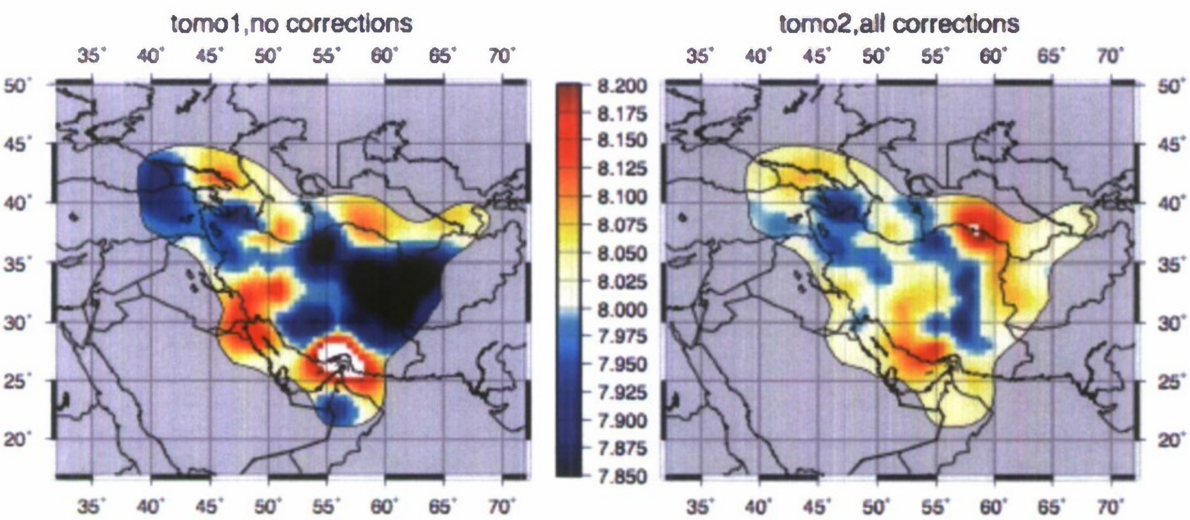

Figure 9. Left) Tomographic results when neither cluster nor station corrections are applied, compared to Right) tomographic results when both cluster and station corrections are applied. Same dataset as Figure 8.

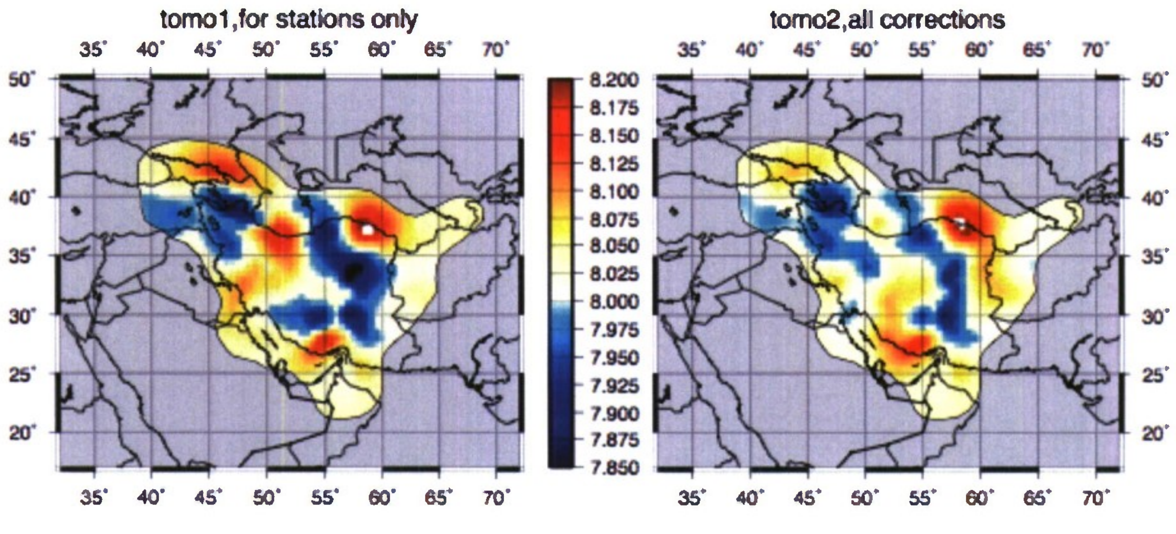

Figure 10. Left) Tomographic results when station corrections, but no cluster corrections, are applied, compared to Right) tomographic results when both cluster and station corrections are applied. Same dataset as Figure 8.

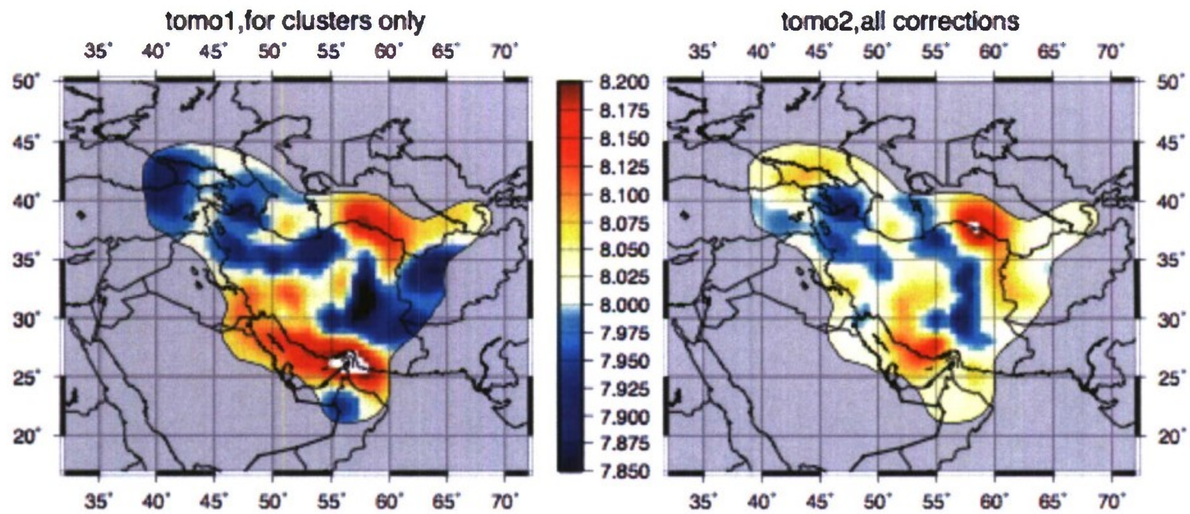

Figure 11. Left) Tomographic results when cluster corrections, but no station corrections, are applied, compared to Right) tomographic results when both cluster and station corrections are applied. Same dataset as Figure 8.

Qualitatively, tomography using station corrections but no source corrections appears rather similar to the result when using all corrections (Figure 10), while tomography using source (cluster) corrections without station corrections leads to an image of *Pn* velocity variations that differs significantly from the case of using both source and station corrections (Figure 11). The magnitude of the difference in *Pn* velocities in each pair of cases is about the same, however, and we suspect that the greater apparent importance of station corrections is an artifact of source and station distribution. It is clear that both source and station corrections are needed, and examination of these corrections is a good indicator of data quality problems, such as poor calibration of a cluster or erroneous station coordinates or timing problems.

Contribution of Moho depth variations

If *Pn* tomography is performed assuming a flat-layered Moho, any actual variations in Moho depth will cause variability in *Pn* arrival times that will be mapped into *Pn* velocity variations. To estimate the degree to which this

could occur in the study region we calculated travel times through a model with variable Moho depth based on observed topography, and compared their variability with that of the observed dataset of calibrated *Pn* travel times.

To generate a model of Moho depth variability we converted topography to Moho depth through the assumption of full isostatic compensation. With reasonable assumptions about density contrast, the surface topography (low pass filtered at a wavelength of 100 km) transforms into inverse Moho depth variations that are larger by a factor of 5.

The variability of observed *Pn* arrival times from our GT dataset is shown in Figure 12, and the variability of *Pn* travel times through the model with artificial Moho undulations based on observed topography and the assumption of full isostasy is shown in Figure 13. Note that the same horizontal scale is used for both plots. The raypaths through the model with undulating Moho were based on the actual source locations of events in the GT dataset and actual stations in the study region.

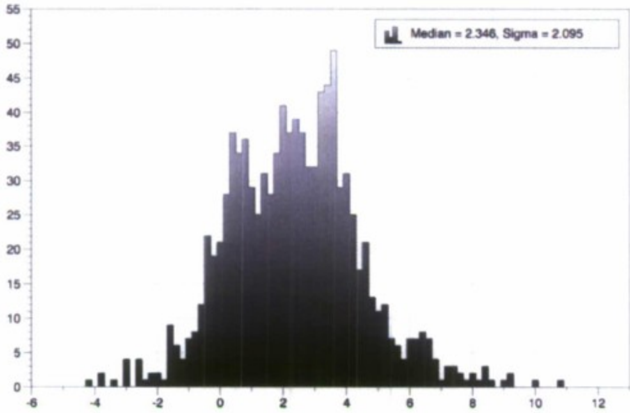

Figure 12. Histogram of residuals for *Pn* arrivals at less than 10° epicentral distance from the GT dataset.

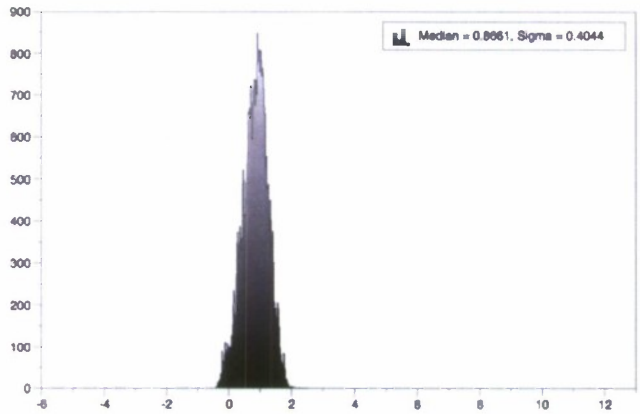

Figure 13. Histogram of residuals for synthetic *Pn* phases traced through the model with Moho undulations based on observed topography and the assumption of full isostatic compensation. Same horizontal scale as Figure 12.

The variance of *Pn* arrival times through the model with undulating Moho $\sigma^2 = 0.16$ is only about 4% of the variance of the observed dataset ($\sigma^2 = 4.38$). Therefore Moho variability is a minor component of the observed variability of *Pn* travel times in the study region. The major factors in the observed variability must be related velocity variations in the crust and upper mantle, departures of raypaths from the geometric assumption, errors in cluster calibration, and errors in phase identification.

CONCLUSIONS AND RECOMMENDATIONS

At this point of the project we have assembled a catalog of seismicity that incorporates a large amount of in-country phase readings. Most earthquakes were carefully relocated in a single event process. We continue to develop this catalog, but it is already a good dataset for use in general tomographic studies of the region. We have also developed

28 calibrated clusters of earthquakes, containing over 800 $GT5_{90}$ events, which are well enough distributed to permit useful tomography to be conducted using only events with calibrated locations and origin times, and datasets of phase readings that have been carefully reviewed and filtered for outliers in a multiple event location analysis. We continue to add new calibrated clusters. Our initial tomographic studies have been concerned with developing a suitable baseline model for tomography. Existing models are generally too fast (theoretical *Pn* arrivals are early by 2–4 seconds). A model similar to ak135 with 45 km thick crust and somewhat slower crustal velocities appears to be a good candidate for the baseline model but further testing is needed. When using our GT dataset for tomography, it is advantageous to parameterize source corrections as cluster corrections (applied to all events in the cluster) rather than individual event corrections. A synthetic experiment suggests that variability of Moho depth in the study region accounts for only a small fraction of the observed variability of *Pn* travel times. The major sources of the observed variability must be velocity varitaions in the crust and upper mantle, perturbations of the raypaths by lateral heterogeneity, and errors in location calibration and phase identification.

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We have received invaluable assistance in this work from numerous colleagues in the study region who prefer to remain unnamed.

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